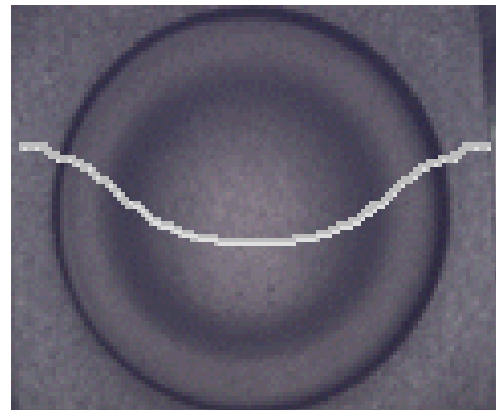


# Electrostatic Doping of Ultrathin Films

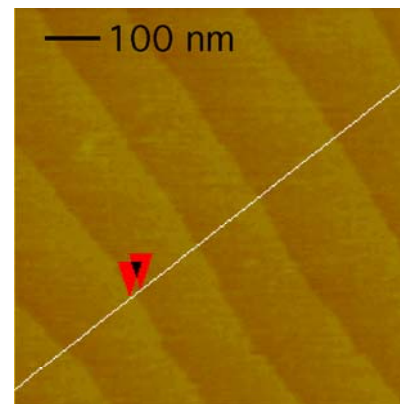
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There is broad interest in studying correlated electron systems that exhibit a variety of interesting phases at low temperatures as a function of carrier density. An alternative to chemical doping is capacitive charging, where a gate voltage in the field-effect geometry induces carriers in the material of interest. In contrast with chemical doping, capacitive charging does not introduce disorder. We have developed micro-machined and surface treated single crystal strontium titanate that can double as a substrate and a gate dielectric. We have achieved charge transfers approaching  $10^{14} \text{ cm}^{-2}$ . These structures are being used to study various quantum phase transitions in both ultrathin metal films and in superconducting and magnetic oxides.

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The back of a micro-machined substrate. A typical height profile is superimposed on the picture. Thickness in the middle can range from  $10\mu\text{m}$  to  $100\mu\text{m}$ , with surface roughness of approximately  $1\mu\text{m}$ . The diameter of the thinned region is typically  $4\text{mm}$ .



Atomic force microscope image of the growth (front) surface of an STO substrate showing unit cell steps with atomically smooth terraces.

There exist a variety of interesting materials with potential technological applications where changing the number of charge carriers (electrons or holes, the latter referring to deficiencies of electrons) can cause significant changes in their properties. Traditionally studies of these materials have involved growing samples with slightly different chemical compositions, which in turn changes the carrier concentration. However, one drawback to this method is that, in addition to modifying the carrier concentration, other variables are also changed. We have developed a technique that permits us to change the carrier concentration (and thus the physical properties) of thin films by employing an electric field effect. In the field effect geometry, films are grown on top of an insulating layer, and a voltage applied across the insulator changes the amount of charge in the material on top of the insulator. This is the basis for the field-effect transistors that run computers. In traditional field effect devices, there is a limit as to how many carriers can be induced before the insulating layer breaks down. The number of induced carriers is 100-1000 times less than the amount needed to produce a change in the properties of the materials we want to study. We have developed a novel insulating structure made of single crystal strontium titanate (STO) to use for modulating properties of thin films.

This work developed from attempts to reproduce some of the results claimed by the notorious H. Schoen, who victimized the scientific community with fraudulent results claiming he had built field effect devices producing some of the largest charge modulations ever reported and, with these devices, he could alter the properties of materials. His work appeared to create a significant opportunity for science and technology, as the approach could result in electrical control of exotic materials, switching them between insulating states (which do not allow current to flow) and superconducting states (which allow current to flow without energy loss). After significant effort we became convinced that Schoen's work could not be duplicated, but sought to develop another approach to electrically tuning the properties of materials by adding or removing charge.

Thin films of many complex materials, such as cuprates, a class of high temperature superconductors, and manganites, materials with large changes in resistance in response to applied magnetic fields, grow easily on top of single crystals of STO. Other investigators have used STO films as the insulating layer for field effect devices. However, the insulating properties of the STO thin films are not as good as those of STO single crystals. Also because STO thin films are not as smooth as single crystal STO, which can be chemically treated to produce atomically flat surfaces, the quality of materials grown on top of STO films is lower. We wanted to develop a method to retain the pristine crystal surfaces of STO single crystals and take advantage of the enhanced insulating properties of single crystal STO. The challenge is that single crystal STO substrates are thick, and the number of charge carriers that we can induce with a given voltage decreases as the STO crystal thickness increases.

The trick to this work was developing a technique to produce micro-machined and surface treated single crystal STO that doubled as a substrate for growing high quality thin films and as the insulating layer in a field effect geometry. By developing a method to thin the STO single crystals, we produced an STO membrane that was thin enough to permit significant modulation in the number of charge carriers, enough to alter the properties of materials, and approaching the level of charge modulation claimed by Schoen. The micromachining technique is “low tech,” in that it involves careful “sandblasting.” Future directions could involve developing ion or chemical -etching techniques, which would be needed for this approach to be used in technology where it would be necessary to scale up to many devices on a single substrate. We are actively using these structures in our research that involves tuning the properties of materials.

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## **Education:**

This work involved a graduate student, Melissa Eblen-Zayas, a postdoctoral associate, Dr. Anand Bhattacharya, and an undergraduate Neal Staley. Ms. Eblen-Zayas was an NSF pre-doctoral fellow and now holds a University of Minnesota Graduate Dissertation Fellowship. Dr. Bhattacharya is now at Argonne National Laboratory, and Mr. Staley is now a first year graduate student at Penn State University. The technique for thinning single crystal strontium titanate substrates was developed by Mr. Staley.

## **Societal Impact:**

The devices that can be implemented using this “platform” can in principle be prototypes for three-terminal superconducting devices and devices in which the magnetization of a film is altered electrostatically. These are potential building blocks in a future electronics technology.